

# Turbulence Spectra in the Noise Source Regions of the Flow Around Complex Surfaces

William A. Olsen and Donald R. Boldman  
*Lewis Research Center*  
*Cleveland, Ohio*

June 1983

LIBRARY COPY

SEP 13 1983

LANGLEY RESEARCH CENTER  
LIBRARY, NASA  
HAMPTON, VIRGINIA

**NASA**

TURBULENCE SPECTRA IN THE NOISE SOURCE REGIONS OF THE  
FLOW AROUND COMPLEX SURFACES

William A. Olsen and Donald R. Boldman

National Aeronautics and Space Administration  
Lewis Research Center  
Cleveland, Ohio 44135

SUMMARY

The complex turbulent flow around three complex surfaces was measured in detail with a hot wire. The measured data include extensive spatial surveys of the mean velocity and turbulence intensity and measurements of the turbulence spectra and scale length at many locations. This paper completes the publication of the turbulence data by reporting a summary of the turbulence spectra that were measured within the noise source locations of the flow.

The results suggest some useful simplifications in modeling the very complex turbulent flow around complex surfaces for aeroacoustic predictive models. The turbulence spectra also show that noise data from scale models of moderate size can be accurately scaled up to full size.

INTRODUCTION

The noise generated by a turbulent airstream passing over the wings and flaps of conventional- and short-takeoff-and-landing (CTOL and STOL) aircraft and other complex surfaces is of practical interest. A number of these surfaces have been studied acoustically in detail. However, the complex turbulent flow around these complex surfaces has neither been measured in detail nor related to the measured acoustic data. The authors, in a previous paper (ref. 1), reported on the turbulence and mean flow parameters that affect the noise level and radiation pattern of three vastly different complex surfaces. An approximate acoustic analogy model was used to estimate the size and location of the volume and surface noise sources. The three surfaces and related noise source contours are reproduced from reference 1 in the three figures in this report.

This short report completes the publication of the turbulence data by reporting a summary of the extensive turbulence spectra that were measured within the noise source regions. These data and the accompanying discussion will suggest some simplifications that will be helpful in applying a basic aeroacoustic theory to the complex flows around complex surfaces. They will also aid in scaling up acoustic data from small models of these surfaces to the full-scale configuration.

BRIEF DISCUSSION OF APPLICABLE BASIC AEROACOUSTIC THEORY

The state of the art in analytically describing the complex turbulent flow around complex surfaces and the resulting noise emission is summarized

E-1669

N83-30168\*

here. Fundamental theories exist for the noise produced by simple flows around simple surfaces. These theories describe the following: the small-chord airfoil, the infinite plate with intense turbulent flow over a leading or trailing edge or with no edges in intense turbulence, and the simple subsonic jet (see the appendix of ref. 1, and ref. 2, for details). The theory for the small-chord airfoil is the nearest to predicting the entire noise emission (i.e., spectra at all angles) without resorting to empiricism (ref. 3). Some fundamental theories only predict, in a simple way, the radiation pattern (e.g., ref. 4). There are of course a large number of semiempirical theories that give more complete predictions (e.g., ref. 5).

The noise generated by the complex turbulent flows around complex surfaces, such as the three surfaces sketched in figures 1 to 3, has certainly not been described by a fundamental theory. Indeed, the mean flow and the details of the turbulence have not even been accurately described by an analytical model. Again, a number of semiempirical theories give a fairly complete description of a range of surface geometries (refs. 6 and 7). A more fundamental model is desirable because it should be able to handle a greater range of configurations. A number of simplifications are required in order to measure and analytically describe the details of these complex flows in a tractable manner. Although some of the simplifications used herein may appear to be extreme, they will not affect the basic conclusions reached.

The simplifying assumptions are as follows:

(1) The spatial gradients of the parameters describing the flow and turbulence are small enough so that single values of the parameters can be used within each source region of the flow. The longitudinal parameters are mean velocity  $U_1$ , rms turbulence velocity  $\tilde{u}_1$ , and integral scale length  $\ell_1$ . Furthermore, the noise reaching a point in the far field is the sum of the noise from all of the volume elements that make up the noise source regions. Therefore, the effect on the resulting far-field noise of even large local deviations from single values of the turbulence parameters would tend be washed out. We shall show later that this is probably a good approximation.

(2) The longitudinal turbulence spectra can be adequately measured by a single wire (normal to the velocity vector) in the manner of Laurence (ref. 8). He found that in external turbulent shear flows two-wire correlations for  $\ell_1$  agreed with single-wire measurements of  $\ell_1$ , where the peak value of the longitudinal turbulence energy  $F_{1p}$  was used instead of the conventional value at zero wavelength. The length scale, using the terminology of reference 9, is

$$\ell_1 = \frac{\pi}{2} R_5 F_{1p} \quad (1)$$

This single-wire technique makes detailed turbulence measurements in the noise source regions near the complex surfaces tractable.

#### APPARATUS AND PROCEDURE

Hot-wire surveys were made in the turbulent flows around the three complex surfaces shown by the sketches in figures 1 to 3. The effective size of all of the nozzles was 5.2 cm. Most of the measurements were made in the

plane through the nozzle center (plane of symmetry), where there is no spanwise mean flow. A tuft was used to align the wire normal to the mean velocity vector at other spanwise measurement locations. Most of the measurements were taken with a single wire to obtain longitudinal mean flow and turbulence data ( $U_1$ ,  $\tilde{u}_1$ , and  $\ell_1$  and normalized spectra). The measurement locations are denoted in the sketches by small circles within the flow region. A few measurements were taken with X wires of the transverse turbulence velocity  $u_2$  and its spectrum; the locations where this was done are denoted in the sketches by small squares. The data measurements, the procedures, and the data reduction follow standard practice; for more detail refer to references 1 and 9.

## RESULTS AND DISCUSSION

### Magnitude and Location of Source Regions

The main purposes of this study were to make detailed turbulence spectra measurements within the noise source regions and to see what these data suggest. Before proceeding any further, the relative magnitude, size, and location of the noise sources must be determined. This can be done by using the simplifying assumptions stated previously and the simple acoustic analogy model described in reference 1. This model is described briefly here so that the reader will have a better physical understanding of the noise sources. From reference 1 the noise amplitude in the far field is the sum of the contributions from the volume and surface noise sources at each point within the turbulent flow field. The amplitude of the volume and noise sources at each point in the flow  $I$  are given by the following equations:

Volume sources (source always present wherever there is turbulence)

$$I \propto V_n^8 \left( \frac{\tilde{u}_1}{V_n} \right)^8 \frac{1}{\ell_1} \quad (2)$$

Surface sources (surfaces with edges immersed in significant turbulence)

$$I \propto V_n^a \left( \frac{U_1}{V_n} \right)^{a-2} \left( \frac{\tilde{u}_1}{V_n} \right)^2 \left( \frac{1}{\ell_1} \right) \left( \frac{r_0}{\ell_1} \right)^{-3} \quad (3)$$

where  $a$  is 6 for very small-chord airfoils,  $c/\ell_1 < 1$ ;  $a$  is 5 for very large-chord airfoils,  $c/\ell_1 > 10$ ;  $V_n$  is the nozzle jet velocity; and  $r_0/\ell_1$  is the distance from the edge of the surface to a given point within the turbulent flow field. These equations show that the magnitude of the volume and surface sources at each point in the flow depends primarily on the mean velocity and the turbulence intensity  $\tilde{u}_1/V_n$  there. The resulting noise source regions are shown by contours on the sketches in each figure. These constant-noise-source contours were copied from reference 1. The surface source is only strong near an edge, where  $r_0/\ell_1$  is large.

A radiation pattern is associated with each source as a factor multiplying 1. It depends on the geometry and the local mean flow in the source region. For example, the volume sources of the configurations in figures 1 and 2 would be mainly radiated in the downstream direction. A velocity power law of  $V_n^8$  or better would be expected in that direction, especially for the over-the-wing configuration, where the volume source is dominant over the surface source. In contrast, the three-flap configuration is dominated by the surface source and the chord length is relatively small. Therefore, the  $V_n^6$  velocity power law would be expected at every angle. The velocity power law results noted in the figures qualitatively show how the pattern varies with geometry and mean flow.

### Magnitude of Parameters Within Source Regions

It was suggested before that each source region might be adequately described by single values of the turbulence parameters, thereby providing a simple quantitative description of the whole complex turbulent flow around the complex surfaces. Values of these single parameters were obtained by merely comparing the noise source regions to the contour plots in reference 1 for  $\tilde{u}_1/V_n$  and  $U_1/V_n$  and the point values of  $\ell_1$ . Table I shows the range of values of these parameters that occurred within the strong source regions (i.e., typically within the -5-dB contours for the volume surface sources).

Single values of the turbulence parameters could be used for each source region because the range of the values for  $\tilde{u}_1/V_n$  and  $U_1/V_n$  is sufficiently small. The scale length variation is much larger, but the effect of the scale length on the magnitude is weak. Therefore, a single value could be used.

### Turbulence Spectral Measurements

Longitudinal turbulence spectra  $F_1 < R_5 k_1 >$  were measured at many locations in the turbulent flow around the three surfaces. A representative sample of these spectra is plotted in figures 1 to 3. These spectra have been normalized by a vertical shift so that the peak energies coincide as defined by equation (4).

$$\frac{4F_1 < k_1 R_5 >}{F_{1P}} \quad (4)$$

where  $R_5$  is a constant set here at the hydraulic radius of the nozzles ( $R_5 = 2.6$  cm). The wave number at the peak  $k_e$  was used to normalize the frequency according to equation (5).

$$\frac{k_1}{k_e} = \frac{2\pi f}{U_1} \left( \frac{4\ell_1}{3} \right) = \frac{2\pi}{3} (R_5 k_1) F_{1P} \quad (5)$$

where

$$k_1 = \frac{2\pi f}{U_1} \quad (6a)$$

and

$$\frac{1}{k_e} = \frac{4\ell_1}{3} \quad (6b)$$

The spectra in the three figures were measured at a large number of points in the flow. For example, the spectrum marked with solid circles in figure 2 was measured (as the sketch shows) at a point well downstream of the trailing edge.

Examination of the three figures reveals that there are basically two types of spectra: The spectra associated with the open symbols have no definite peak except at zero frequency; the spectra associated with the solid symbols have a definite peak. In most cases the peaked spectra occurred within the secondary turbulent mixing region of the flow coming off the trailing edge of the surface.

### Discussion of the Spectra

Having described the spectral data, we now discuss the significance of the spectral results. In particular, what simplifications are suggested that would permit improvements in aeroacoustic analytical models? And finally, what do these results suggest with regard to scaling up acoustic data from small-scale models?

Simplifications in aeroacoustic models. - Above  $k_1/k_e = 1$  nearly all of the longitudinal spectra were within  $\pm 1$  dB of the Kolmogoroff law ( $k_1^{5/3}$ ) or the exponential law ( $k_1^2$ ). These laws are for the nonviscous inertial sub-range. The  $k_1^7$  law applies where viscous effects dominate (ref. 10). These laws also describe the limited number of transverse spectra measured.

We must now relate the turbulence spectra to the acoustic spectra for this model size (5.2-cm nozzle). The normalized frequency  $k_1/k_e$  is related to the Strouhal number used in acoustics  $fd_n/V_n$ .

$$\frac{k_1}{k_e} = \frac{2\pi f}{U_1} \frac{1}{k_e} = \frac{8\pi}{3} \left( \frac{\ell_1}{d_n} \right) \left( \frac{V_n}{U_1} \right) \left( \frac{fd_n}{V_n} \right) \quad (7)$$

where  $d_n$  and  $V_n$  are the nozzle diameter and velocity, respectively, and  $U_1$  is the local mean velocity. Equation (7) is then evaluated approximately by using typical values for  $\ell_1/d_n$  and  $\tilde{u}_1/V_n$  from table I:

$$\frac{k_1}{k_e} \cong 5 \left( \frac{fd_n}{V_n} \right) \quad (8)$$

For a velocity range of 120 to 240 m/sec the normalized frequency  $k_1/k_e$  range would be from 0.4 to 40 for an acoustic frequency range of 200 to 40 000 Hz.

Within this range nearly all of the normalized turbulence spectra on the three plots collapse together (within  $\pm 1$  dB). In other words, a single normalized turbulence spectrum describes all of the points within the source regions, over the range of the acoustic data for the model ( $0.4 < k_1/k_e < 40$ ).

But what about the few points where there is a very peaked spectrum that does not match the single universal spectrum. A unique characteristic in the turbulence spectral data permits a good check on the previous claim that single values of  $\tilde{u}_1/V_n$ ,  $l_1/d_n$ , and  $U_1/V_n$  and a single curve for the normalized spectra will describe the turbulent flow for complex surfaces adequately for acoustic modeling purposes. A large region of the flow for the model over-the-wing configuration (fig. 2) had a strong peak that persisted at higher velocities. Indeed, the turbulence spectrum described by the solid triangles was the most peaked spectrum observed. Spanwise spectral measurements show that this region was about half a nozzle width wide. Such a large region must surely generate a noticeable peak in the far-field acoustic spectra. Nevertheless there was no evidence of even a weak peak in the acoustic spectra near the frequency of this peak. In other words, the noise emitted from other points in the source regions, with somewhat different turbulence parameters, was enough to swamp out this peculiar peaked source region. This result again suggests that little would be gained by modeling the turbulent flow in detail; single values of the turbulence parameters are sufficient for each source region. This does not mean that peaked acoustic spectra cannot occur. A small cylinder has a region of intense highly correlated turbulence in its near wake; it produces a very peaked acoustic spectrum (ref. 3). But keep in mind that peaked turbulence spectra would become less peaked as the size of the surface or velocity (i.e., Reynolds number) was increased (ref. 8).

A universal normalized turbulence spectrum would tend to produce a universal acoustic spectrum at  $90^\circ$  from the direction of the mean flow through the source region. The  $90^\circ$  was selected to remove mean velocity effects. Normalized acoustic spectra from these types of complex surfaces do indeed tend to collapse together.

Scaling up acoustic data from a model. - Examination of fundamental aero-acoustic theories for jet and surface noise indicates that small-scale-model acoustic data can be simply scaled up to full scale (at the same  $V_n$ ). Scaling requires that the square of the ratio of model diameter to microphone radius  $(d_n/R)^2$ , the ambient temperature, and the attenuation be accounted for and also that the model and full-scale Strouhal number  $fd_n/V_n$  and normalized turbulence spectra be the same. The normalized turbulence spectra for the model and full-scale configurations will agree if viscous effects are not important. The three plots show that viscous effects are only important above a normalized frequency of  $k_1/k_e = 100$ , where the turbulence spectral law changes from  $k_1^{-5/3}$  (nonviscous) to  $k_1^{-7}$  (viscous effects dominate). Corresponding to  $k_1/k_e = 100$  is a Strouhal number of about 20. Because this is much higher than the upper limit of the acoustic model data, acoustic model data with a 5-cm nozzle are safely below the viscous-dominated region. Full-scale data may be a problem because the acoustic data go up to 20 kHz. But these data are also below the viscous region because the transition (nonviscous to viscous) increases with the Reynolds number to the 0.75 power (ref. 9).

Recent comparisons of scaled-up model data from complex surfaces agreed within 1 to 2 dB with full-scale data, except at low velocities, where the internal engine fan noise affected the full-scale noise at high frequency.

## CONCLUDING REMARKS

The results given in this report suggest some useful simplifications in modeling the complex turbulent flow around complex surfaces for aeroacoustic predictive models. Even with these simplifications the authors believe that the state of the art in applying fundamental aeroacoustic theory to complex surfaces is not sufficiently advanced to predict the noise emission without considerable empiricism. On the other hand, noise data from scale models can be simply and accurately scaled up. Therefore until significant improvements are made in applying fundamental aeroacoustic theory and in modeling the complex turbulent flow for use in these theories, it is simpler and more accurate to measure the noise from a small-scale model and scale up the data.

## REFERENCES

1. Olsen, W. A.; and Boldman, D.: Preliminary Study of the Effect of the Turbulent Flow Field Around Complex Surfaces on Their Acoustic Characteristics. AIAA Paper 78-1123, July 1978.
2. Goldstein, M.: Aeroacoustics. McGraw Hill Book Co., Inc., 1976.
3. Olsen, W. A.: Noise Generated by Impingement of a Turbulent Flow on Airfoils of Varying Chord, Cylinders, and Other Flow Obstructions. AIAA Paper 76-504, July 1976.
4. Goldstein, M.: Scattering and Distortion of the Unsteady Motion of Transversely Sheared Mean Flows. J. Fluid Mech., vol. 91, pt. 4, 1979, pp. 601-632.
5. Tam, C. K.; and Yu, J. C.: Trailing Edge Noise. AIAA Paper 75-489, Mar. 1975.
6. Fink, M. R.: A Method for Calculating Externally Blown Flap Noise. NASA CR-2954, Mar. 1978.
7. Zorumski, W. E.: Aircraft Noise Prediction Program, Theoretical Manual. NASA TM-83199, 1982.
8. Laurence, J.: Intensity, Scale and Spectra of Turbulence in Mixing Region of a Free Subsonic Jet. NACA TR-1292, 1956.
9. Boldman, D. R.; and Brinich, P. F.: Mean Velocity Turbulence Intensity and Scale in a Subsonic Turbulent Jet Impinging Normal to a Large Flat Plate. NASA TP-1037, 1977.
10. Hinze, J.: Turbulence. McGraw Hill Book Co., Inc., 1959.



# APPENDIX - SYMBOLS

$a$	exponent in eq. (3)
$c$	airfoil chord length, m
$d_n$	nozzle diameter, m
$F_1 < k_1 R_5 >$	turbulence energy in narrow frequency band 6 Hz wide
$F_{1p}$	peak value of turbulence energy spectrum
$f$	frequency, Hz
$I$	sound intensity
$k_e$	wave number at peak value of turbulence energy
$k_1$	wave number, $k_1 = 2\pi f/U_1$
$\ell_1$	longitudinal integral length scale, m
$R$	microphone radius, m
$R_5$	normalizing size, taken here as hydraulic radius of nozzle
$r_0$	distance from edge of surface to point within flow field, m
$U_1$	local longitudinal mean velocity, m/sec
$\tilde{u}_1$	root-mean-square component of longitudinal turbulence velocity, m/sec
$V_n$	nozzle velocity, m/sec

TABLE I. - RANGE OF VALUES OF  $\tilde{u}_1/V_n$ ,  $U_1/V_n$ , and  $\ell_1$   
WITHIN STRONG SOURCE REGIONS ( $\geq -5$  dB)<sup>a</sup>

Configuration	Surface sources	Volume sources
Slotless wing	Trailing-edge region: $0.12 < \tilde{u}_1/V_n < 0.14$ $0.6 < U_1/V_n < 0.8$ $? < \ell_1 < 1.8$ cm	Trailing-edge region: $0.14 < \tilde{u}_1/V_n < 0.16$ $0.4 < U_1/V_n < 0.6$ $0.9 < \ell_1 < 1.9$ cm  Impingement region: $0.15 < \tilde{u}_1/V_n < 0.16$ $0.4 < U_1/V_n < 0.6$ $1.5 < \ell_1 < 1.8$ cm
Over the wing	Trailing edge: $0.1 < \tilde{u}_1/V_n < 0.13$ $0.8 < U_1/V_n < 0.9$ $? < \ell_1 < ?$	Near trailing edge: $0.16 < \tilde{u}_1/V_n < 0.18$ $0.4 < U_1/V_n < 0.6$ $1.3 < \ell_1 < 1.4$ cm
3-Flap	Trailing edge of last flap: $0.1 < \tilde{u}_1/V_n < 0.12$ $0.5 < U_1/V_n < 0.7$ $0.7 < \ell_1 < 1.0$ cm  Between flaps: $0.1 < \tilde{u}_1/V_n < 0.13$ $0.6 < U_1/V_n < 0.8$ $1.6 < \ell_1 < 1.8$ cm	Above trailing edge: $0.15 < \tilde{u}_1/V_n < 0.16$ $0.4 < U_1/V_n < 0.6$ $0.9 < \ell_1 < 1.4$ cm

<sup>a</sup>Where  $\tilde{u}_1$  is root-mean-square component of turbulence velocity,  $V_n$  is nozzle velocity,  $U_1$  is local mean velocity, and  $\ell_1$  is integral scale length.

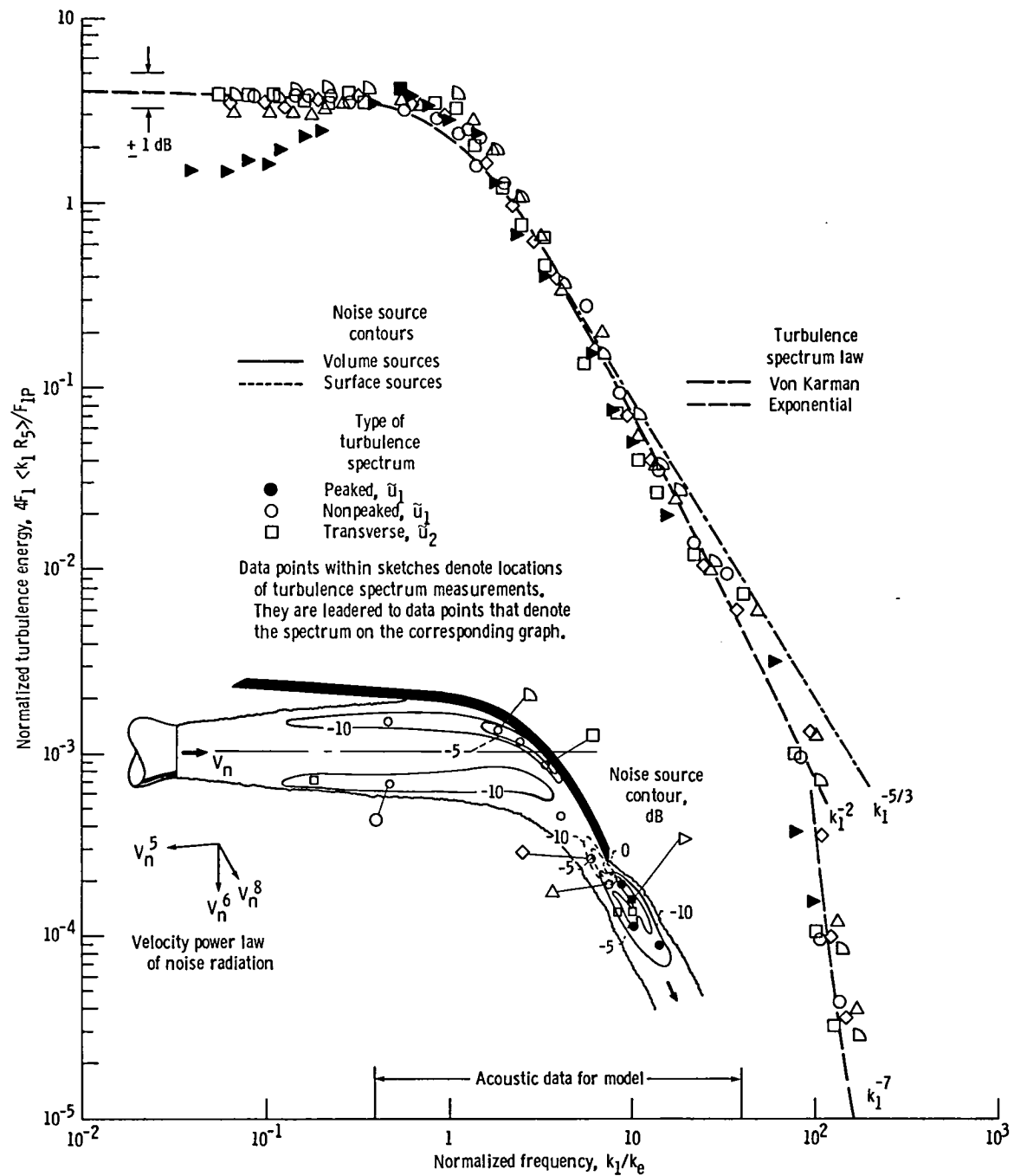


Figure 1. - Turbulence spectra in noise source regions of the slotless wing.

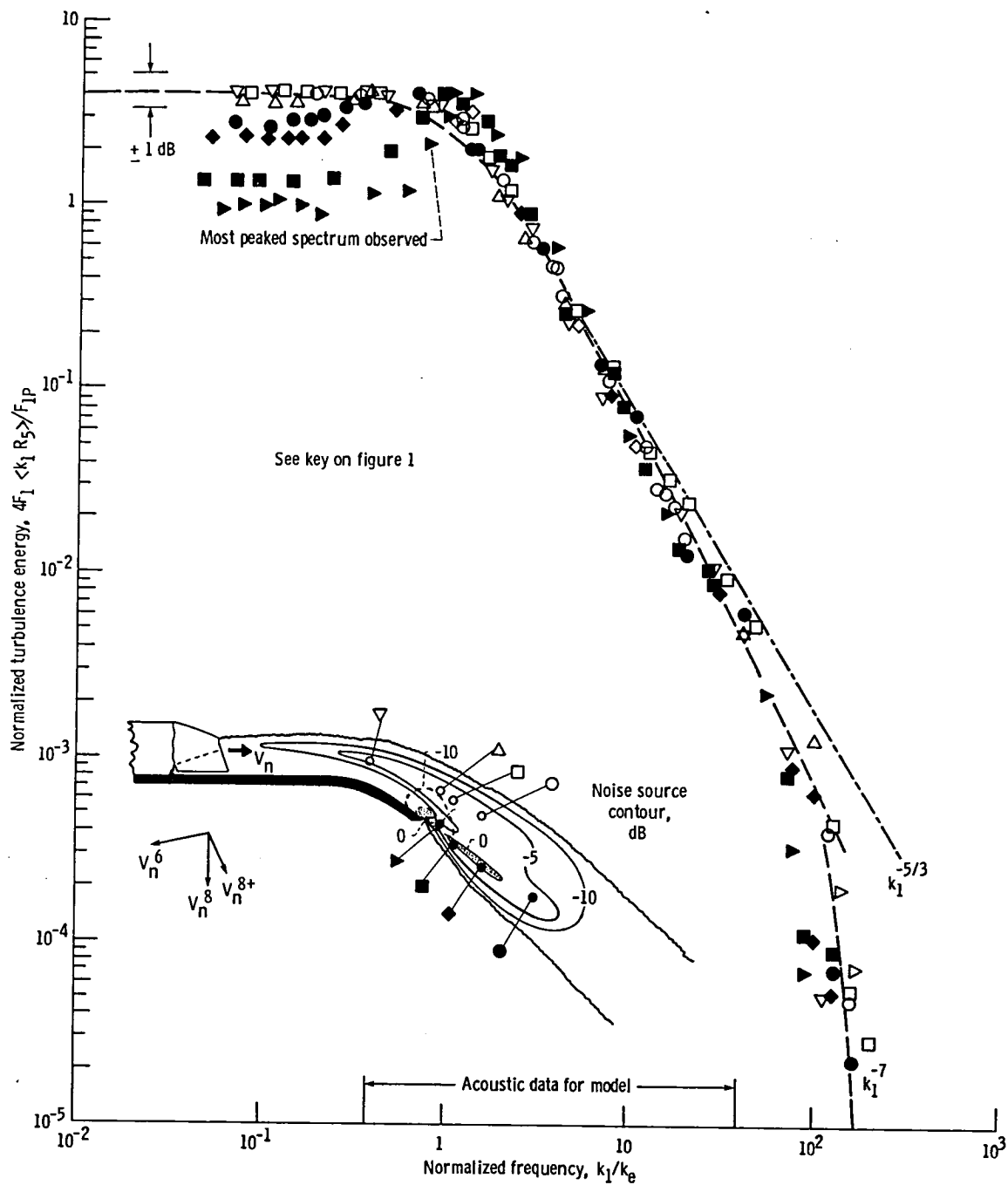


Figure 2. - Turbulence spectra in noise source regions of the over-the-wing configuration.



1. Report No. NASA TM-83392		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle TURBULENCE SPECTRA IN THE NOISE SOURCE REGIONS OF THE FLOW AROUND COMPLEX SURFACES				5. Report Date June 1983	
				6. Performing Organization Code 505-45-02	
7. Author(s) William A. Olsen and Donald R. Boldman				8. Performing Organization Report No. E-1669	
				10. Work Unit No.	
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135				11. Contract or Grant No.	
				13. Type of Report and Period Covered Technical Memorandum	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546				14. Sponsoring Agency Code	
15. Supplementary Notes					
16. Abstract <p>The complex turbulent flow around three complex surfaces was measured in detail with a hot wire. The measured data include extensive spatial surveys of the mean velocity and turbulence intensity and measurements of the turbulence spectra and scale length at many locations. This paper completes the publication of the turbulence data by reporting a summary of the turbulence spectra that were measured within the noise source locations of the flow. The results suggest some useful simplifications in modeling the very complex turbulent flow around complex surfaces for aeroacoustic predictive models. The turbulence spectra also show that noise data from scale models of moderate size can be accurately scaled up to full size.</p>					
17. Key Words (Suggested by Author(s)) Turbulence spectra External flows Acoustic scaling			18. Distribution Statement Unclassified - unlimited STAR Category 71		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of pages	
				22. Price*	

National Aeronautics and  
Space Administration

Washington, D.C.  
20546

Official Business

Penalty for Private Use, \$300

SPECIAL FOURTH CLASS MAIL  
BOOK



Postage and Fees Paid  
National Aeronautics and  
Space Administration  
NASA-451

**NASA**

---

POSTMASTER: If Undeliverable (Section 158  
Postal Manual) Do Not Return